Using Iterative Repair to Automate Planning and Scheduling of Shuttle Payload Operations

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Abstract

This paper describes the DATA-CHASER Automated Planner/Scheduler (DCAPS) system for automated generation and repair of command sequences for the DATA-CHASER shuttle payload. DCAPS uses general Artificial Intelligence (AI) heuristic search techniques, including an iterative repair framework in which the system iteratively resolves conflicts with the state, resource, and temporal constraints of the payload activities. DCAPS was used in the operations of the shuttle payload for the STS-85 shuttle flight in August 1997 and enabled an 80% reduction in mission operations effort and a 40% increase in science return.

Introduction

Generating command sequences for spacecraft operations can be a laborious process requiring a great deal of specialized knowledge. Typically, spacecraft command sets are large, with each command performing a low-level task. There are often many interactions between the commands relating to the state of the spacecraft. In addition, due to spacecraft power and weight limitations, the resources available on-board spacecraft are often scarce. These factors in combination make manual generation of command sequences a difficult process. Because of the importance and expense of this process, tools to assist in planning and scheduling spacecraft activities are critical to reducing the effort (and hence cost) of mission operations.

This paper describes the DATA-CHASER Automated Planner/Scheduler (DCAPS) which was used to command, schedule, and reschedule the DATA-CHASER shuttle payload.

DCAPS uses search algorithms for two problems: initial schedule generation, and schedule repair/refinement. In initial schedule generation, DCAPS generates a default schedule to perform science observations from the null schedule (i.e., an empty schedule), supporting domain specific and randomized initial schedule generation strategies. In schedule repair or refinement, DCAPS accepts an existing schedule with conflicts (i.e., resource oversubscriptions, state conflicts, etc.) and performs modifications to make the schedule consistent with the spacecraft constraints. DCAPS implements this functionality by using "iterative repair" search techniques (Zweben et al. 1994). Basically, this technique iteratively selects a schedule conflict and performs some action in an attempt to resolve the conflict. In iterative repair mode, DCAPS is well adapted for human interaction. In this mode, a user can move, add and delete activities in order to alter the schedule to their preferences. DCAPS can then be invoked to repair state, resource, and temporal constraints caused by these modifications. In this fashion, scientists who need not be spacecraft and sequence engineer experts can perform command sequence generation. This allows the scientist to become directly involved in the command sequencing process. Additionally, if there are changes in the spacecraft state (e.g., faults) or user-defined goals (e.g., science opportunities), the repair algorithm allows simple rescheduling that attempts to minimize disruption of the original schedule. Finally, the highly restrictive payload resources and constraints are constantly monitored and conflicts automatically avoided.

The sequence generation problem addressed by DCAPS includes both planning and scheduling according to typical Artificial Intelligence definitions. DCAPS performs planning in that it determines appropriate actions to achieve state and resource values required to satisfy goals. It performs scheduling in that these selected activities must be temporally placed to comply with (aggregate) resource, state, and timing constraints required by the operations constraints.

The DCAPS system was developed for operation of the DATA-CHASER shuttle payload, which was developed and managed by students and faculty of the University of Colorado at Boulder. DATA-CHASER is a science payload, with a primary focus on solar observation. The main activities for the payload involve science instrument observations, data storage, communication, and control of the power subsystem. Science activities are performed using three solar observing instruments: the Far Ultraviolet Spectrometer (FARUS), Soft X-ray and Extreme

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Ultraviolet Experiment (SXEE), and Lyman-alpha Solar Imaging Telescope (LASIT). These are imaging devices that collect data at various wavelengths.

The payload resources include power, tape storage, local memory, the three instruments, and the communication bus. DATA-CHASER is also constrained by externally driven states such as the shuttle orientation and external events such as shuttle waste material, which affect when certain science activities can be scheduled. Payload activities must be sequenced while avoiding or resolving conflicts. The DCAPS system models all of these states and resources, as well as the state and resource requirements and effects of activities. This model enables automation of command generation for the DATA-CHASER payload.

The remainder of this paper is organized as follows. First, we describe the DATA-CHASER shuttle payload and mission objectives. Next, we describe how the payload is modeled. We then describe in detail the DCAPS approach to automated command sequence generation and repair. Then, we describe how DCAPS fits in to the overall flight and ground system architecture for the DATA-CHASER mission. We then describe the experience and results from the use of DCAPS during the STS-85 flight. Finally, we discuss related work and conclusions.

DATA-CHASER Payload

DATA-CHASER consists of two synergistic projects, DATA and CHASER, which flew as a Hitchhiker (HH) payload aboard STS-85 on the International Extreme Ultraviolet Hitchhiker Bridge (IEH-2) in August 1997 (Rabideau et al. 1996). A technology experiment, DATA (Distribution and Automation Technology Advancement) demonstrated advanced semi-autonomous, supervisory operations. CHASER (Colorado Hitchhiker and Student Experiment of Solar Radiation) was a solar science experiment that served to test DATA. The DATA technologies support cooperative operations distributed between different geographic sites as well as between humans and machines, on-board autonomy, human control, and ground automation.

CHASER consists of three co-aligned instruments that take data in the far and extreme ultraviolet wavelengths. The first and oldest of these instruments (17 years old) is FARUS, which takes a continuous spectrum from 115 nm to 190 nm with a resolution of .12 nm. LASIT takes images of the full solar disk of the sun in the Lyman-alpha wavelength (121.6 nm) with a Charge Injected Device imager. The final instrument in the scientific package, SXEE, consists of four photometers, each having a different metallic coating so as to enable them to look at different wavelengths between 1 and 40 nm. The objective of these instruments is to measure the full disk solar ultraviolet irradiance and obtain images of the sun in the Lyman-alpha wavelength, providing a correlation between solar activity and radiation flux as well as an association of Lyman-alpha fluxes with individual active regions of the sun.

The flight segment of the DATA-CHASER project consists of a canister that is equipped with a Hitchhiker Motorized Door Assembly (HMDA), which houses the instruments and their support electronics. The second canister contains the flight computer for the payload as well as the 2 GB Digital Audio Tape (DAT) drive that is used to store all data that is collected during the mission. The payload data is also sent to the ground system through both low rate (available 90% of the time, at 1200 bps) and medium rate (available when scheduled, at 200 kbps). The payload is also capable of receiving commands sent from the ground system when uplink is available.

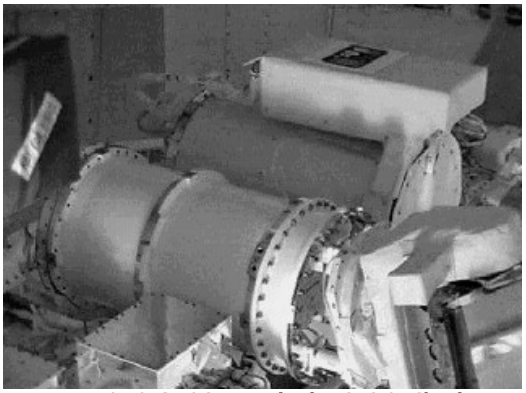
Often, DATA-CHASER was in a passive mode monitoring its state and notifying the ground of any changes. When the orbiter bay was pointed at the sun, the DATA-CHASER payload was in solar active mode where all instruments take data.

The data is both written to the DAT drive on board and downlinked to the ground system for immediate data analysis. Several times during the mission, DATA-CHASER took data while not pointing at the sun. This data is to test various portions of the DATA experiment with non-solar-pointing data in addition to being used for instrument calibration.

One of the consequences of flying on the shuttle system is that shuttle resources are shared and, hence, limited, with availability subject to change every 12 hours (the frequency at which NASA changes shuttle flight plans). These resources include access to uplink and downlink channels, and time that the payload is allowed to operate. In addition, a payload typically has thermal constraints, which would limit the duration of payload exposure to the sun (or away from the sun). Any given payload may also have environmental constraints that restrict the payload state and activities when shuttle contamination events are occurring.

In addition to modeling the internal constraints and resources of the payload, DCAPS would also search the shuttle flight plan for times when the payload was allowed to operate, downlink data, uplink new command sets, and when scientific instruments had to be protected from contamination events.

DATA-CHASER was an interesting scenario for



Picture 1: DATA-CHASER Payload in STS-85 Shuttle Bay

scheduling because of the complex data and power management involved in the science gathering. An automated scheduler must find an optimal "data taking" schedule, while adhering to the resource constraints. In addition, the scientists would like to perform dynamic scheduling during the mission. As an example, the summary data may indicate the presence of a solar flare. If this occurs, scientists have different requirements and goals, such as higher priorities on certain instruments or longer integration times. These new goals may require a different schedule of activities.

Modeling the Payload

In order to use the DCAPS system, the user must write a software model of the mission activities and spacecraft resources. DCAPS uses the Plan-IT II (PI2) system (Eggemeyer, 1995) to model the spacecraft activities and constraints, thus the model is expressed in the PI2 modeling language. Modeling in the PI2 language involves defining a set of objects and describing how they interact. These definitions are then used by the scheduler to create instances of the objects and reason about specific interactions (e.g., state and resource conflicts) in the schedule. The two major types of objects in the model are *activities* and *resources*.

Activities

Activities are used to model the events that affect the DATA-CHASER payload and the actions that the DATA-CHASER payload can take. All activities have a duration and a set of parameters. In addition, some activities may have a set of subactivities. For these activities, the user can also define a set of temporal constraints between the subactivities. Examples of activities in the DCAPS model include: Tracking and Data Relay Satellite System (TDRSS) contacts and turning the CHASER heater on and off (CHASER-heater-on and CHASER-heater-off). Another activity, SXEE-Scan-Step, has four sensor read steps as subactivities.

Resources

Resources define the various physical resources and the constraints they impose. There are five essential types of resources: state, concurrency, depletable, non-depletable, and simple.

State resources are used to model payload systems with discrete operating states. For each state resource, the modeler must specify the possible values for the state variable. Most of the systems have at least one state variable, which represents whether or not they are activated. Shuttle orientation is also modeled as a state variable.

Concurrency resource constraints are used to model rules that stipulate that an activity either must occur during another activity or cannot occur at the same time as another activity. One relationship that is modeled with a concurrency resource is the requirement that a downlink or uplink can only occur during contact with a TDRSS satellite. This is modeled as a resource that is present when there is TDRSS contact activity and required when there is a downlink or uplink activity.

Depletable resources are used to model aggregate resources with a fixed quantity, such as fuel or RAM. Activities can use some finite amount of a depletable resource, which may or may not be restorable. The amount used by the activity is persistent to the end of the schedule. In addition, the modeler must specify a maximum capacity for each depletable resource. In DCAPS, an onboard memory buffer is modeled as a depletable resource. Science observations produce data and use some amount of the depletable resource. Other activities, such as a transfer to permanent storage, may restore this resource.

Non-depletable resources are used to model aggregate resources with a limit to the usage at any one time, but are reset at the end of the activity that consumes the resource. Similar to depletable resources, nondepletables are assigned a maximum capacity. Power is modeled as a non-depletable resource.

Simple resources are used to model devices that can only be used by one activity at a time. For instance, each of the instruments on board DATA-CHASER (FARUS, SXEE, and LASIT) is capable of taking only one image at a time and is modeled with simple resources.

The DATA-CHASER model uses 67 resources and 58 activity types. The payload required 7 resources to model the impact of exogenous events such as shuttle contamination events, day/night cycles, shuttle maneuvers, and other external activities which impact payload operations. The payload also required 6 resources to represent possible failed states for major instruments/subsystems. For each instrument, a number of resources would be required. For example, for SXEE, there are 6 resources. One resource represents the instrument itself. Two resources are required to represent the instrument door – one for the open/closed state and another for the closing process which draws power. A SXEE-failure resource represents whether the instrument is known to have failed (and hence disables the scheduler from scheduling any SXEE activities). A SXEE-power resource tracks the power consumption of the SXEE instrument, and a SXEE-relay resource models the hardware relay used to enable/disable the SXEE instrument. In addition to the instruments, there are a number of system-wide resources to be tracked by DCAPS. Total power consumption and energy usage (for thermal considerations) are tracked for each canister. Finally, science and engineering data must be processed through a set of 3 buffers onboard the spacecraft as well as the secondary storage DAT tape drive.

The DATA-CHASER model also contained a significant number of activity types (58). Of these, the vast majority (25) were hardware control commands. Fourteen commands related to the acquisition of science and engineering data, and 6 commands controlled the downlink

capability (TDRSS, medium-rate, and low-rate). Nine (9) commands were used to represent possible subsystem failures (e.g., to disable use of certain instruments and subsystems). Seven (7) activities were used to represent exogenous events (such as medium rate downlink coverage, solar pointing for the shuttle bay, etc.). The activities can also be viewed from an instrument centric perspective. From this viewpoint, the SXEE instrument has commands to: transfer SXEE data from the SXEE instrument to the general instrument buffer, open and close the SXEE instrument door, control the SXEE-relay which enables use of the instrument, take a sun scan, take a dark scan (with the instrument door closed for calibration purposes), and perform several of the typical steps to take and transfer the data to storage.

The DCAPS Automated Planner/Scheduler

The DATA-CHASER Automated Planner / Scheduler was part of the DATA-CHASER mission operations software. It was a ground-based intelligent tool used for developing a schedule of commands for uplink to the payload (Rabideau et al. 1996). The DCAPS system was used for initial schedule generation and interactive schedule repair.

During initial schedule generation, DCAPS produces a complete, valid schedule of payload operation commands from a model, initial state, and set of high-level goals. In the interactive repair phase, it takes intermediate, invalid schedules (resulting from user changes) and produces a similar, but valid schedule.

The DCAPS consists of: the Plan-IT II (PI2) sequencing tool (Eggemeyer, 1995) and the schedule reasoner. PI2 was originally designed as an "expert assistant sequencing tool." PI2 includes a GUI that allows for easy manipulation of the schedule. In addition, it serves as an activity/resource database that tracks activities and their constraints using a model of the payload in the PI2 modeling language (as described above). The schedule reasoner uses PI2 to automatically generate new schedules, repair existing faulty schedules, and optimize valid schedules. PI2 provides information about resource availability and conflicts; the scheduler must decide which activities to use to resolve the conflicts and where to place the activities temporally.

Schedule Data-Base

PI2 continually monitors activities in the sequence. As activities are added or moved, the change in resource usage is automatically updated, and the new resource profiles are displayed. With this information available, the user can immediately see the effects of a schedule change on the mission resources. For each resource, PI2 also monitors any conflicts that are occurring on the resource.

Conflicts are time intervals where the limitations of the resource have been exceeded. Finally, PI2 monitors any dependencies that have been defined between activities and resources. The values of specific parameters of activities and resources may be functionally dependent on values of other parameters. PI2 automatically keeps these parameter values consistent.

PI2 also helps out by serving as an activity and resource database, producing/accepting information to/from a sequencer. The functional interface to PI2 has been extended to better assist an automated sequencer. A basic set of "fetch" functions has been developed to quickly retrieve information about conflicts as well as the resources and activities involved in the conflict. For example, an interface function has been written to fetch the legal times where an activity can occur in the schedule. Here, "legal times" refers to positions where no conflicts are caused by any of the resources used by the given activity.

In addition to fetching information about the current state of the schedule, the user will need to be able to change the current state in attempt to fix or optimize the schedule. Some basic primitive functions are provided by PI2 to allow an external system to add and move activities, change their duration, etc. These primitives make up the set of actions that a scheduler can take when trying to resolve conflicts.

Schedule Reasoner

The second major component of DCAPS is the automated schedule reasoner. Implemented as an extension to PI2, the schedule reasoner provides three capabilities: initial schedule generation, schedule repair, and schedule optimization. In initial schedule generation, a schedule is generated from a set of user requested activities. In schedule repair, the scheduler will automatically restore the consistency of the sequence after arbitrary user interaction by rescheduling using local repair actions. The schedule

```
buildInitialSchedule()
    turn on the two canisters 2 hours into the mission
    and leave them on for the duration (cmds DataRelayOn,
    ChaserRelayOn)

    for each interval in which the shuttle is pointing at the sun and
    there is no contamination event
        open the hitchhiker door (HMDAOpen) at the start of the interval
        close the hitchhiker door (HMDAClose) at the end of the interval

    for each interval in which the shuttle is not in a solar pointing state for
    longer than 30 minutes
        turn on the canister heater 30 minutes after the solar pointing
        turn off the canister heater at the beginning of the next solar
        pointing interval

    loop until no legal times for a data-take (FARUS, SXEE, or LASIT)
        find legal times for the data-take  (during the solar pointing non-
        contamination events)
        place the data-take at the earliest possible start time
        place a DAT transfer after the data-take
```

Figure 1: Domain specific initial schedule generation

repairer iteratively attempts to resolve each conflict, which involves making choices on what to repair and how to repair it. In a more advanced extension to iterative repair, schedule optimization can be performed. In this technique, portions of the schedule are examined and possibly rescheduled to improve part of the schedule that may not contain conflicts.

Initial Schedule Generator—The first step in sequencing spacecraft commands is to come up with an initial schedule of events for each phase of the mission. DCAPS supports two modes for automated initial schedule generation: a domain specific schedule generation algorithm and a randomized scheduling algorithm. The domain specific scheduling algorithm is shown in Figure 1. In this approach, the scheduler inserts necessary setup activities (powering on the payload and controlling the payload doors) and schedules an even mix of observations by sweeping forward in time. However, little effort was devoted towards optimizing this approach.

DCAPS also supports a randomized initial schedule generation algorithm. In this approach, the scheduler merely uses random placement to attempt to place science observations. As expected, this approach performs significantly worse than the domain specific approach.

Schedule Repairer—The generated initial schedule may still violate some of the spacecraft constraints. Also, the scientists and engineers might feel that their goals were not completely satisfied or that they could be better achieved by an alternate plan. In these cases the users want to be able to interact with and modify the generated schedule. These modifications may introduce new conflicts into the schedule. The schedule repair capability can automatically repair these introduced conflicts, freeing the user from this burden and reducing overall mission operations effort. Additionally, freeing the user of the burden of low-level repair allows the user to spend more time modifying the schedule – allowing the combined user/software system to explore more of the schedule space.

Before describing the schedule repairer, we must present a few definitions. A "conflict" is a violation of one of the resource constraints. A conflict occurs over a certain time period and is caused by activities called "culprits." For example, if the power capacity is exceeded from time t_1 to time t_2, then a conflict exists from time t_1 to time t_2, and the culprits are any activities that use power and overlap the interval $[t_1, t_2]$.

There are three possible actions to take in attempt to resolve a conflict: move, add, or delete an activity. The "move" action involves moving one of the culprits of the conflict to a position that will either resolve the conflict or at least ensure that the moved activity is no longer a culprit. Some conflicts can be resolved by adding a new activity. These activities usually provide some resource that was previously not available. Finally, a conflict can also be resolved by simply deleting the culprits. This is obviously not a preferred method and is only used as a last resort.

The resolution of a conflict greatly depends on the type of resource that is in violation. There are five different types of conflicts corresponding to the five types of resources. A *state conflict* occurs when an activity requires the resource to be in a state different from its current state. The culprits in this type of conflict are all of the activities that require the incorrect state and the activity that changed the resource to the incorrect state. Several possibilities for resolving a state conflict include moving the culprits to another interval where the required state is present or adding an activity that will change the state of the resource to the required state.

A *concurrency conflict* is when an activity requires the presence of the resource during a time for which it is absent. The culprits in this type of conflict are all of the activities that require the presence of the resource. To resolve a concurrency conflict, the scheduler can move the culprits to an interval where the resource is present or add an activity that provides the presence of the resource.

A *depletable conflict* means that the activities of the schedule have used too much of the resource. In this type of conflict, the culprits are all activities that use the resource before the point of overflow. Some depletable resources have "resetter" activities and this sort of conflict can be resolved by adding an activity that "resets" the available resource. For example, a downlink activity will free up space in the downlink buffer.

A *non-depletable conflict* occurs when activities overuse a resource during a particular time interval. The culprits in this type of conflict are all of the activities that use the resource during the conflict interval. This sort of conflict can be resolved by moving or deleting culprits. There are no activities in the DATA-CHASER model that can replenish a non-depletable resource.

Simple conflicts occur when two or more activities use the same simple resource at the same time. This type of conflict can only be resolved by moving or deleting culprits.

Given an initial schedule, the schedule repairer must find the correct activities to move, add, or delete and position them temporally in such a way that no conflicts remain. The scheduler relies on some interface functions to PI2 that describe the conflicts in the current schedule, describe the activities that could resolve a conflict, and manipulate the schedule. The schedule repair algorithm is an iterative loop with the following choice points:

1. conflict selection,
2. selection of a method to resolve the conflict from one of: move, add, or delete,
3. selection of an activity to which to apply the chosen method, and possibly
4. temporal placement of the moved or added activity (i.e., start time and duration).

In Table 1, we outline the heuristics implemented within DCAPS for each of these choice points (the heuristic method actually used is marked with an asterisk). After the chosen action is performed, the schedule repairer

Choice Point	Heuristics
Conflict Selection	Highest priority (determined by resource)
	Highest contention (oversubscription)
	Most culprits
	Largest duration
	Least culprits*
	Smallest duration
Operation selection (move, add, or delete)	Random
Activity selection for Move	Move culprit which contributes most to conflict*
	Move culprit with least temporal flexibility
	Move lowest priority
Activity selection for Add	Add activity that reduces conflict most*
	Add the activity which has the fewest legal times
	Add highest priority
Activity selection for Delete	Delete culprit that contributes most to conflict
	Delete the culprit which participates in most conflicts*
	Delete lowest priority
Time selection	Choose latest start time
	Choose earliest start time
	Choose latest start time for state conflicts and earliest start time for resource conflicts*

Table 1: Heuristics implemented for each choice point

checks to see if progress was made (defined as decreasing the number of conflicts, decreasing the number of culprits, or decreasing the duration of the conflicts). If the action did not succeed in resolving the conflict, or progress was not made, then the action is retracted. Otherwise, conflicts are recomputed and the loop counter is incremented. This process continues until all conflicts are resolved, or the loop counter exceeds a user-defined maximum bound. For every choice point in the algorithm, where a selection must be made from a list of possibilities, the schedule repairer is allowed to backtrack to that point. What this means is, that if a particular choice fails, the schedule repairer may choose another from the list before giving up. If all choices fail, then a previous decision must have been incorrect, and the repairer can backtrack to the preceding choice point. All choice points, including the decision on whether or not to backtrack, are heuristic decisions and may be customized to a particular domain.

Schedule Optimization — Often there may be many legal schedules, all of which are not equally preferred by the users. In the extreme case, the empty schedule (e.g., do nothing, or some schedule of this form) is usually a legal schedule. In the DATA-CHASER mission, the dominant quality measure is science return - which can be roughly measured by the number of science measurements taken and downlinked in the current planning cycle. In order to improve the quality of the DCAPS-produced schedules, we implemented a simple schedule optimization algorithm that accepts as input an oversubscribed schedule. This algorithm first expands all of the activities into the lowest level (because the most detailed resource modeling may allow a more densely packed schedule). The algorithm then performs a forward sweep through the schedule in which each activity is moved to its earliest start time. This has the effect of packing the activities towards the start of the schedule potentially opening room for the extra activities towards the end. In the DATA-CHASER case, the oversubscribed activities are science data-takes and the oversubscription is due to over-use of the instrument, communications bus, and buffer resources. The schedule optimization algorithm takes an oversubscribed schedule and packs in the science observations more closely – thus allowing further science observations to fit into the schedule. This optimization algorithm can be viewed as a simplified version of the schedule packing algorithm described in (Aldas, 1997) and the doubleback algorithm described in (Crawford, 1996).

Application Development, Deployment, and System Integration

DCAPS was developed by the JPL Artificial Intelligence group as part of a set of early prototypes of automated planning and scheduling engines for use by NASA's New Millennium Program. Later, when the DATA-CHASER mission operations automation problem was studied, we determined that the iterative repair capabilities of DCAPS would be well suited for mixed-initiative partially automated, human in the loop, shuttle payload operations. At this time DCAPS was modified to meet a number of minor user interface requirements and the DATA-CHASER model was constructed over a series of software spirals with each model increasing in coverage and fidelity. The total JPL AI Group effort involved in the development of DCAPS and initial modeling was approximately 1.4 work-years. The total effort by CSGC to deploy the DCAPS system was on the order 0.4 work-years.

DCAPS was integrated into the End-to-End Mission Operations System (EEMOS) used for the DATA-CHASER portion of the STS-85 payload. This EEMOS architecture is also being evaluated as part of the Fire and Ice pre-project (Siewert & Hansen, 1996). The DATA-CHASER EEMOS consisted of seven parts: Command and Control, Fault/Event Detection Interaction Reaction (F/EDIR), DATA/IO (Data handling), the Ground Database, the Graphical User Interface, the software testbed, and finally the DCAPS planner.

The command and control language used, System Command Language (SCL, also known as Spacecraft Command Language), integrates procedural programming with a real-time, forward-chaining, rule-based system. DCAPS interfaces with SCL through DATA/IO by sending script scheduling commands to be scheduled either on the flight or ground system. This interface is implemented by

mapping PI2 activities to SCL scripts that were written prior to flight and can be scheduled or event-triggered by activating rules. A list of these scheduling and rule activation commands is then sent to DATA/IO which forwards the list to the SCL Compiler. Once compiled, the list is sent to the payload through the next available uplink.

DCAPS is also interfaced with the ground EEMOS database, O2. O2 is an object-oriented database used to store all mission data and telemetry that is downlinked by the payload. O2 also stores a command history. Through DATA/IO, DCAPS requests current payload status data in the form of sensor values in the telemetry history. It also requests lists of all commands uplinked during a given time interval. These are used by DCAPS to infer command completion status as well as to get the current state of the payload so that a new schedule can be created.

During mission operations, approximately every six hours, DCAPS was asked by an operator to generate script scheduling commands and rule activations for the next six hours. This list was then reviewed by the Mission Operations staff on duty. When judged to be correct, scheduling and rule activation commands would be sent to DATA/IO during the next available uplink window. If during that six hour period there was a major change in the NASA activities, the operations staff could use DCAPS to update the schedule script on-board. If so desired, DCAPS could generate an updated command list, ask the user to verify it, and send the list to DATA/IO to be uplinked.

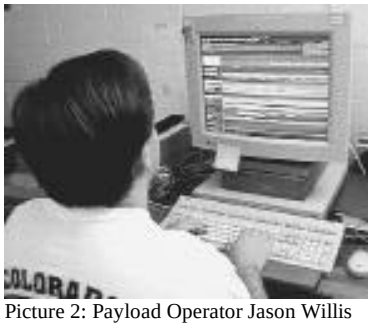
Impact and Results from Use During STS-85

Unfortunately, difficulties were encountered during the development and integration of the real-time DATA-CHASER flight software. Due to these difficulties and hard shuttle payload delivery constraints, the real-time onboard command execution software for the payload did not have several capabilities that were originally designed. First, the onboard software was unable to command the SXEE and LASIT instruments. Second, the onboard software did not have the capability to store and execute time-tagged command loads, thus all operations had to be carefully synchronized with real-time shuttle uplink windows. Third, the onboard tape storage device (DAT) was not functional. This meant that data storage was limited to the onboard solid state buffers. However, since the LASIT instrument was the most significant producer of data by over an order of magnitude, this was not a major problem. The first and second limitations described above meant that having an automated planning system to automatically coordinate the complex timing constraints was even more important; manually attempting to enforce such timing constraints would increase the chance of operator error causing loss of data. Likewise, being able to replan quickly and automatically when shuttle activities changed (such as downlink or uplink windows and solar view periods) was also critical.

Carrying the DATA-CHASER payload, STS-85, the Space Shuttle Discovery, launched at 7:41AM PST on Thursday August 7, 1997. Mission operations, including mission planning and scheduling were performed for the 2 week flight. During the first 5 days of DATA-CHASER operations, DCAPS was used in manual mode. In this mode, activities were placed manually and DCAPS was used to validate constraints, identify constraint violations, and generate the actual command files. During the last 7 days of the payload operation, DCAPS was used to automatically generate schedules. In this phase, the domain specific initial schedule generator was used to generate an initial schedule. Due to network lag times[1], use of the iterative repair techniques was somewhat limited. However, this did not impact operations significantly. In many cases minor conflicts were repaired manually.

The DCAPS automated scheduling capability significantly impacted DATA-CHASER mission operations. DCAPS enabled an 80% reduction in the amount of effort to produce operations plans. Manual generation of a 6-hour operations plan would require from 30 to 60 minutes in manual mode of operations and from 7 to 9 minutes using the DCAPS automated scheduling capability. This reduction in effort is because DCAPS can automatically generate an acceptable or near acceptable schedule very quickly. The number of modifications (if any) to make a DCAPS generated schedule acceptable can be made far faster than manually generating a schedule from scratch. DCAPS also enabled a 40% increase in science return. Manually generated plans had 2-3 instrument scans per viewing opportunity whereas DCAPS generated plans had 3-4 scans per viewing opportunity. This is because DCAPS could directly monitor and track all of the complex timing constraints involved in the instrument activities and pack activities more tightly than operators manually placing instrument activities. During the 7 days of DCAPS automated use, DCAPS scheduled a total of 93 science scans and 202 payload commands.

One significant feature of the DCAPS system is its declarative representation of flight rules and spacecraft constraints. This feature was tested during the STS-85 flight in the following manner. When initial command sequences were uplinked, the flight software rejected a number of commands immediately following a reset command. This was due to the fact that the initial flight rules were constructed with the assumption that payload



Picture 2: Payload Operator Jason Willis uses DCAPS to command the DATA-CHASER Payload

[1] DATA-CHASER was operated primarily from Colorado Space Grant, but because they had limited computing resources, DCAPS was run on JPL machines.

commands could be issued immediately following a reset. Actual operations showed that a delay of 30 seconds was required before the payload could accept commands. When this problem was noticed and isolated, it was a simple manner to quickly update the DCAPS model to require this delay so that future command sequences would execute without problem. This aspect of ease of modification is key in that operating procedures and constraints constantly evolve throughout the mission lifecycle as mission priorities and spacecraft characteristics evolve.

Summary and Related Work

Iterative algorithms have been applied to a wide range of computer science problems such as traveling salesman (Lin & Kernighan, 1973) as well as Artificial Intelligence Planning (Chien & DeJong, 1994, Hammond, 1989, Simmons, 1988, Sussman, 1973). Iterative repair algorithms have also been used for a number of scheduling systems. The GERRY/GPSS system (Zweben et al, 1994, Deale et al. 1994) uses iterative repair with a global evaluation function and simulated annealing to schedule space shuttle ground processing activities. The Operations Mission Planner (OMP) (Biefeld & Cooper, 1991) system used iterative repair in combination with a historical model of the scheduler actions (called chronologies) to avoid cycling and getting caught in local minima. Work by Johnston and Minton (Johnston & Minton, 1994) shows how the min-conflicts heuristic can be used not only for scheduling but for a wide range of constraint satisfaction problems. The OPIS system (Smith 1994) can also be viewed as performing iterative repair. However, OPIS is more informed in the application of its repair methods in that it applies a set of analysis measures to classify the bottleneck before selecting a repair method.

In summary, DCAPS represents a significant advance from several perspectives. First, from a mission operations perspective, DCAPS is important in that it significantly reduces the amount of effort and knowledge required to generate command sequences to achieve mission operations goals. Second, from the standpoint of Artificial Intelligence applications, DCAPS represents a significant application of planning and scheduling technology to the complex, real-world problem of spacecraft commanding. In particular, significant quantitative improvements in operations efficiency were documented during the STS-85 flight. Third, from the standpoint of Artificial Intelligence research, DCAPS mixed initiative approach to initial schedule generation, iterative repair, and schedule optimization represents a novel approach to solving complex planning and scheduling problems.

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